Flywheel-Based Recycling Of Electrical Energy For Grid Frequency Regulation

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Abstract--Beacon Power Corporation has successfully demonstrated flywheel energy storage systems (FESS) operating in demanding telecommunications applications, with over 350,000 hours of operation. Beacon's 6 kWh FESS product has the highest levels of stored energy of any flywheel in commercial operation.

A utility sized FESS using 1MW-250 kWh deployable modules is proposed for providing frequency regulation with low operating cost. The response time of the system is dramatically faster than the current service providers, who rely on varying the output of generators. This energy storage based system uses no fuel and produces no emissions, and can actually recycle energy. In addition to providing frequency regulation, the system can also provide reactive power for local voltage support, provide grid oscillation damping, and stability for distributed and renewable resources.

PJM has evaluated the approach of using this flywheel-based technology and has approved its use within the PJM system. The next step is a field trial using existing lower energy flywheels.

Index Terms—Distributed Resources; Energy Storage; Flexible AC Transmission System; Flywheels; Frequency Control; Reactive Power; Renewable Resources; Transmission system; Uninterruptible Power Systems; Voltage Control

INTRODUCTION

BEACON POWER CORPORATION has successfully demonstrated flywheel energy storage systems (FESS) operating in parallel in demanding telecommunications applications, with over 350,000 hours of successful operation. Beacon's 6 kWh FESS product has the highest levels of stored energy of any flywheel in commercial operation. As an energy storage device, the higher initial cost and lower operating cost characteristics of flywheels will offer the most compelling value proposition where there is a need for "working" energy storage – where the system is charged and discharged frequently.

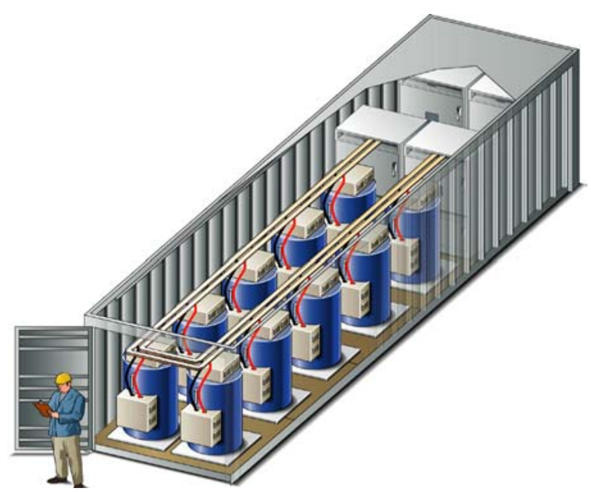

Figure 1. Beacon Full-Scale SEM (250 kWh)

An excellent application with such characteristics has been identified requiring a high-energy flywheel that can address a well-established market with attractive pricing characteristics. This market is the frequency regulation ancillary service supplied to transmission grid systems.

In order to maintain a near constant network frequency, the grid must constantly balance the supply of power generated with the varying demand (load). This balance is maintained today by frequent, small adjustments in the output of some of the generators operating on the grid. Not all generators can be effectively operated with constantly varying output, and all that are operated in this manner are affected negatively due to increased fuel consumption and maintenance.

Frequency regulation has traditionally been a function required of integrated utilities, but with deregulation, it has also become a separately identified service with its own established market price. Frequency regulation is one of several ancillary services that have been viewed as an additional source of revenue for generators that had been originally justified simply on the basis of selling energy. The idea of developing solutions specifically to provide ancillary services may be unconventional, but should be considered if grid reliability, performance, environmental impact, and cost could all be simultaneously improved.

The frequency regulation application provides a perfect match between the attributes of the FESS and the characteristics required. Flywheels actually recycle excess energy when generated power exceeds load and deliver it back to the grid when load increases. Unlike conventional generator-based regulation, no fuel is consumed, and no emissions are generated. This

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characteristic will allow for a greatly simplified and accelerated process for siting and permitting the equipment compared to that of conventional generators.

The Smart Energy Matrix (SEM), shown in Figure 1, has been designed to store enough energy to deliver 1 MW for 15 minutes. The SEM consists of a container housing 10 high-energy flywheels and the necessary electronics to connect to the grid. The devices can easily be deployed and relocated. The SEM can be ganged to deliver 10+ MW systems. The system has a design life of 20 years or more, similar to other utility equipment (and unlike battery based energy storage systems). The power delivery characteristics of both the flywheel and electronics, in a modular configuration, greatly contribute to system reliability. The intrinsically redundant matrix configuration offers high availability since failure of any discrete electrical or mechanical component does not disable the remaining matrix components; the impact is limited to a shorter duration of energy delivery until repairs can be made. These are designed to be performed without shutting the operating flywheels down.

RECYCLING BASED FREQUENCY REGULATION

The frequency regulation market serves to maintain the delicate balance between utility load and power generated. If power generated exceeds load, system frequency increases. Conversely, when power generated is less than the demand load, generators will "slow down" and drop frequency. The expected performance is to keep the system at 60 Hz. Excessive frequency shifts caused by load/generation imbalances have been linked to significant blackout events.

Load changes can be very rapid, even in the sub-second range, whereas generation transients are slow and can lag load variations by minutes. The difference between these two power levels is a major component of an Area Control Error, or ACE. It is typically in the range of 1%-2% of the total power being generated **[1]**. As a result, utilities typically reserve 1-400 MW for frequency regulation.

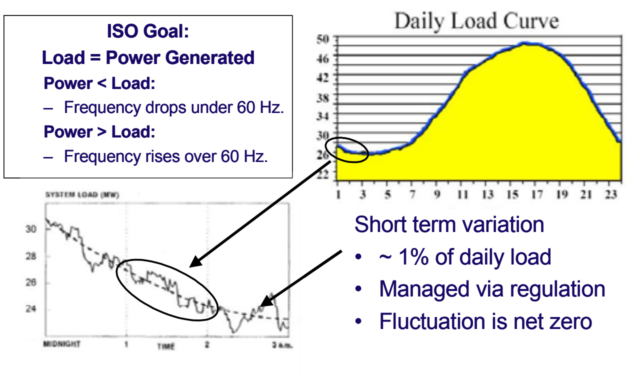


Figure 2. Frequency Regulation Description

Figure 2 shows typical local variation of the load demand curve that is addressed by frequency regulation. It is intended to be a "net zero" short-term correction, on the order of 10-15 minutes where over-generation equals under-generation. This zero-sum characteristic makes this an ideal application for energy storage. In addition, this is a very highly cyclic application because the typical cycle between crossing the neutral point is measured in seconds and minutes. There can be, therefore, tens of thousands of cycles in the course of a year. Normal operation includes constant charging and discharging at varying rates, from very slow to rapid, deep cycling. In this application, the storage device will very rarely be "resting". It is unlikely that any existing chemical based battery system has the required cyclic capability for a 20-year design life.

Traditionally, frequency regulation is accomplished by operating fossil-fuel or hydro generators connected to the electric grid; converting fossil-fuel or hydro reserves into electric energy, often with poor efficiencies and limited to certain geographical locations. The flywheel based system represents a new, easily deployable method in which electric energy is *recycled*; first absorbing it when it is in abundance, then discharging for the desired frequency regulation effect. Durable, low maintenance, high power and energy flywheels can provide fast response, tens of thousands of cycles per year, and offer a footprint small enough to be easily located where needed (typically at substations or load distribution centers in industrial parks).

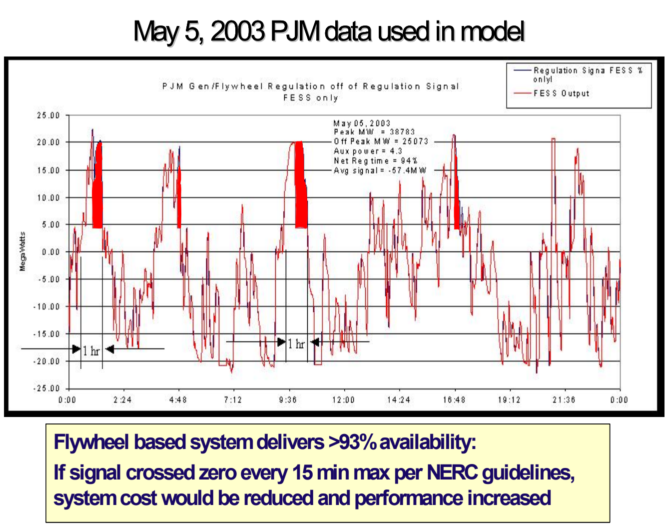


Figure 3. Typical flywheel performance in regulation

Performance modeling results using PJM actual historical regulation data **[2]**, shown in Figure 3, conclude that a modular flywheel system matrix that can deliver a megawatt for 15 minutes provides an effective solution for frequency regulation. The signal in Figure 3 is the control signal from PJM. The red filled areas show where the flywheel ran out of energy and was no longer able to contribute regulation. Note, however, that that condition occurred only after approximately ½ hour constantly calling for power. That ½ hour far exceeds, the 5 to 15 minute guideline for the frequency regulation Ancillary Service set by NERC **[3]**. Performance would have been at, or near, 100% if the regulation signal crossed zero within the guidelines.

The control signal sent to the regulating devices shown in Figure 3, is actually a processed signal that is much slower than the actual load changes. It is slowed down by the ISO to match transient characteristics of the regulating turbines. Figure 4 shows the relationship between load changes and turbine response. Note the time delay of approximately 5 minutes.

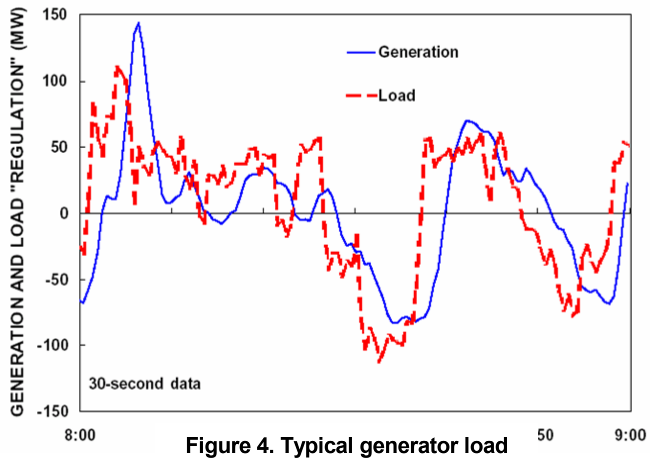


Figure 4. Typical generator load following characteristics [4]

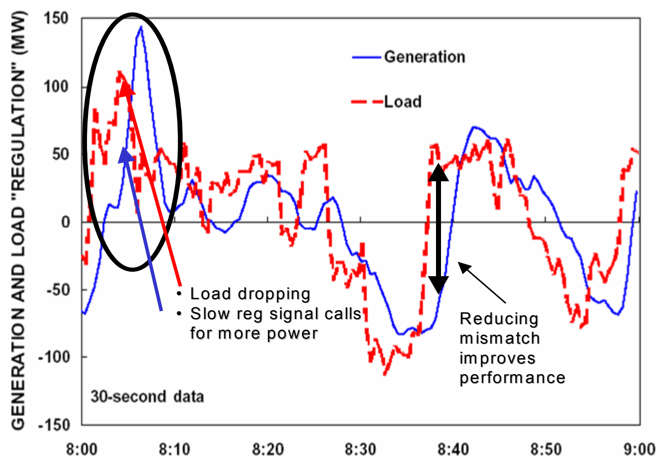


Figure 5. Effect of slow response

Figure 5 shows the classic result of a slow feedback response to this rapid input (load in this case) change. Note that the load is dropping quickly, but the slow signal continues, actually making the frequency regulation problem harder to manage. A faster response offers many advantages. Hydro generating plants are usually much faster in responding (1-2 minute typical delays), and do offer better performance, but this service is often not available behind congested nodes like large cities. Flywheels react well to fast transients and hard, deep discharges. The sub-cycle response is much faster than even hydro and could be located behind congestion points. Detailed analysis still needs to be performed, but it is certain that the faster response can lead to a reduced regulation requirement and therefore, cost.

The idea of using energy storage for frequency and voltage support is not new. There have been several large facilities housing lead acid batteries like the one built in Puerto Rico shown in Figure 6. That facility was designed for 20 MW for 15 min and was cost justified to perform spinning reserves and avoid operating turbines unloaded at idle. When put in operation, it was also used for frequency regulation. The batteries lasted only 2-3 years. They are now being replaced.

Figure 6. PREPA 20 MW Battery Energy Storage System

Since no SEMs have been built to date, Figure 7 shows 40 generator trailers (similar to SEMs) to show what 40 MW for 15 minutes of SEM might look like. The advantage of the flywheel-based installation is clear in real estate size facility complexity. In addition, it is designed for a high cyclic application like this, and would have an expected life of 20 years with minimal maintenance.

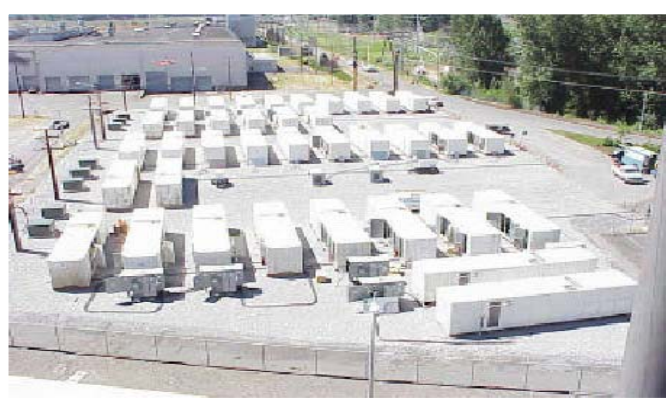


Figure 7. What a 40 MW-15 min. SEM installation would look like [5]

THE ECONOMICS

The cost of this system is very attractive compared to today's generator-based methods, thanks to an uncoupling of fuel cost since energy is recycled in the SEM. Unlike turbines and nuclear plants, flywheels are designed for low cost high cycling capability. The main cost elements consist of depreciation of the flywheel system, lease of the land occupied by the trailer, maintenance, and cost of make-up power associated with system efficiency. Maintenance on this system is minimal and consists of an annual general inspection and of changing air

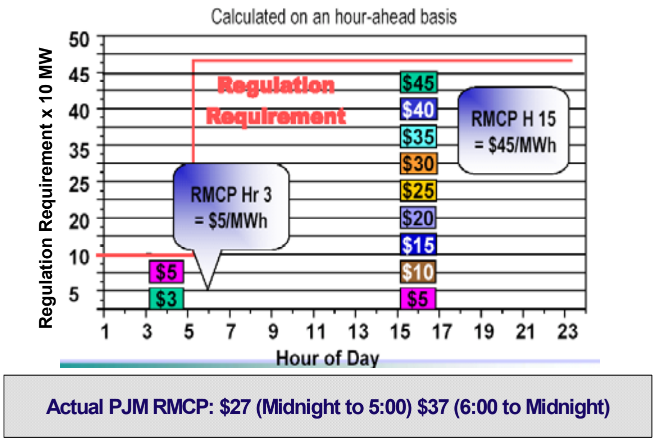


Figure 8. Regulation Marginal Cost Pricing [6]

filters. The flywheels operate in a self-maintaining vacuum chamber using maintenance-free magnetic bearings. The overall efficiency (energy out/energy in) of the total system including electronics, bearings, and flywheel rotor drag is on the order of 85% round trip. The cost of the make-up energy for powerloss is predictable and can be purchased at a low Location Marginal Price.

Frequency regulation is an Ancillary Service that uses a bid system, shown in Figure 8, in the day-ahead and hour-ahead markets. The ISO or RTO determines how much regulation it will need the following day and ask for bids from regulation providers. The RTO then sorts the bids and energy amounts from lowest to highest and takes the bids from the bottom of the list until its energy quota is filled. The price of the marginal bid that met the energy amount is called the marginal price and gets paid to all of the bidders. Figure 8 shows a typical scenario, Clearly, the low cost providers can benefit significantly. The addition of new low cost providers can actually displace the high marginal cost bids and lower the overall system cost to the ISO. The ability to drive the marginal cost down is the main incentive for ISOs to encourage the alternate technologies

OTHER BENEFITS AND PARADIGM SHIFTS

The primary benefit of the SEM is its capability in providing low cost frequency regulation. However, the electronics (described in the Appendix) used in the SEM have the characteristics of providing reactive power to the grid. The controlled injection or absorption of reactive power, with or without a real power component, adds a secondary but important capability to provide voltage support. Further, fast acting control electronics allow for the damping of grid oscillations. When located behind transmission constraints, the multiple functionality of this technology offers the benefits that follow:

- Provide dynamic reactive compensation efficiently where needed.
- Unburden generators from reactive power requirements
- Provide frequency control at a lower cost
- Provide grid oscillation damping
- 15 minutes of backup can allow relaxing contingency and reliability criteria
- Reduce transmission congestion
- Improve voltage stability limits
- All services provided using no fuel and producing no emissions

These benefits do not have identified monetized value with today's tariff structure. However, these issues are key in addressing grid reliability improvements. If SEMs could be included in the rate structure, Transmission companies could improve reliability while providing regulation services.

The value of these benefits would increase as disturbances from renewable and distributed resources are added to the grid.

APPENDIX

Basic Operation

The Smart Energy Matrix (SEM) is composed of an array of energy storage modules (ESM) and energy conversion modules (ECM). Each individual ECM output is in the form of a pair of DC terminals at 750 Volts and is connected in parallel to a common DC bus. As shown in Figure 9, a power conversion module (PCM) converts the flywheel matrix's DC output to AC. A step-up transformer is required between the

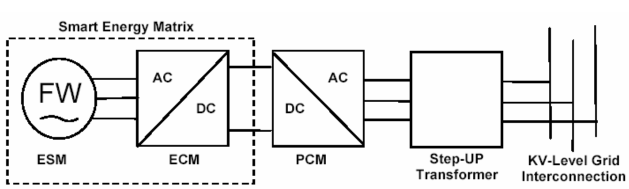
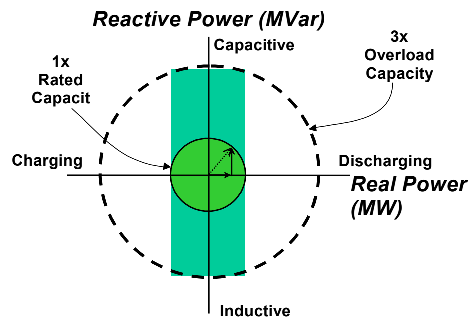
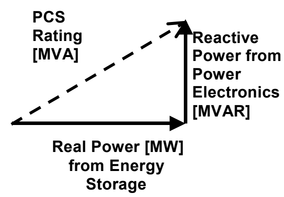


Figure 9. SEM configuration

PCM and the grid interconnection; since the electrical grid interface is an electrical distribution or transmission line at much higher voltage level (i.e. 35, 69, 115 kV). The transformer-electric grid interface is a shunt connection in which the transformer terminals bridges across the phases.

As shown in Figure 10, the SEM and PCM compliment each other by contributing with different complex-power components. The SEM supplies or absorbs real power [W]. Conversely, the PCM injects or absorbs reactive power [VAR]. Although the SEM's circuitry does play a role in reactive power and the PCM in real power; these magnitudes are relatively small. The SEM+PCM combination can effectively operate in all four quadrants of the real/reactive power space. The sum of both, the real and reactive components, is bounded by the complex power capacity of the PCM and step-up transformer, which is measured in volt-amperes [VA]. The frequency regulation function only requires real power injection/absorption; the voltage regulation function will typically require reactive power injection/absorption alone. However, transient voltage events have been proven to be effectively damped by both real and reactive power injection.





	MVAR	MW
(green)	Cont	15 min
(teal)	Seconds	--
Function	Volt Reg	Freq Reg

Figure 10. Relationship of Real and Reactive Power

REFERENCES

[1] PJM Website http://www.pjm.com/documents/reports.html

[2] PJM data located on clearing price report on website www.pjm.com

[3] B.J. Kirby, J. Dyer, C. Martinez, et. al., "Frequency Control Concerns in the North American Electric Power System", December 2002, report coordinated by the Consortium for Electric Reliability Technology Solutions CERTS.

[4] Eric Hirst "Standard Market Design for Regulation" presentation September 2002. Consultant in Electric-Industry Restructuring ORNL

[5] Cesar Amicarella, "Role of Rental Services in Improving Productivity" presentation by GE Energy Rental Services

[6] PJM Report "10_MOC_Ancillary_Services.pdf" Ancillary Services